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Wave-induced fluid flow effects related to porous rocks containing spatially continuous variations of the physical properties

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The classical version of the theory of poro-elasticity assumes that wave-induced fluid movements at the macroscopic scale, as defined by the prevailing wavelengths, are the only causes of seismic velocity dispersion and attenuation in porous media. Correspondingly, the probed material is implicitly supposed to be homogeneous at the microscopic and mesoscopic scales and all poro-elastic moduli are real-valued and independent of frequency. However, there is consistent evidence to demonstrate that, on their own, the physical mechanisms of classical poro-elasticity are unable to account for the attenuation behavior inferred from seismic observations. There is also increasing evidence indicating that structural and/or compositional heterogeneity at the mesoscopic scale is likely to be capable of explaining much of the excess attenuation observed in real data. Numerical modeling of poro-elastic seismic wave propagation in the presence of mesoscopic heterogeneity is particularly difficult. For this reason, most available work on this topic considers simplified geometries, such as periodically layered, binary distribution of the physical properties of the rock frame and/or the saturating pore fluids or mixtures of two porous phases characterized by a single dominant length scale. While such models have greatly contributed to a better conceptual understanding and quantification of the observed attenuation of seismic waves in porous media, they are often inadequate to account for specific geological and/or petrophysical details of a given situation. A primary reason for this is that to a first approximation many, if not most, typical porous rocks are characterized by continuous, scale-invariant distributions of the hydraulic and elastic material parameters as well as by continuously varying saturation levels. Mesoscopic heterogeneity of this type is not amenable to direct numerical modeling and we therefore address this problem through a suitable upscaling procedure. The corresponding computational approach emulates a laboratory experiment, in which a representative mesoscopic rock sample is subjected to a time-harmonic compressibility test. The thus observed complex volume change of the probed sample then allows for estimating the equivalent complex plane-wave modulus, which in turn yields the corresponding equivalent phase velocity and quality factor as functions of frequency. We apply this approach to a range of canonical models of porous media characterized by realistic mesoscopic heterogeneities associated with the hydraulic and/or elastic properties as well as varying levels of saturation. In particular, we also compare the results of spatially continuous variations of the medium and fluid properties with corresponding binary parameter distributions. Interestingly, preliminary results provide evidence to suggest that for most heterogeneous porous media characterized by spatially continuous variations of the hydraulic and/or elastic properties, the contribution of wave-induced fluid flow effects to the velocity dispersion and attenuation of seismic waves is much less significant than commonly assumed based on evidence from conventional approaches.